

COMMONLY OBSERVED DEGRADATION IN FIELD-AGED PHOTOVOLTAIC MODULES

M. A. Quintana and D. L. King, Sandia National Laboratories
T. J. McMahon and C. R. Osterwald, National Renewable Energy Laboratory

ABSTRACT

Degradation leading to failure in photovoltaic modules follows a progression that is dependent on multiple factors, some of which interact causing degradation that is difficult to simulate in the lab. This paper defines recently observed degradation in field-aged modules, including degradation of packaging materials, adhesional loss, degradation of interconnects, degradation due to moisture intrusion, and semiconductor device degradation. Additionally, this paper suggests that the onset and progression of degradation need to be studied to gain a more comprehensive understanding of module degradation rates and module failures.

INTRODUCTION

Photovoltaic modules are system components that convert solar radiation directly to electricity. Having established the function of the modules, there are design and operational attributes such as safety, cost effectiveness, reliability, and aesthetics that are required in order to meet specific applications. Predicting the reliability of photovoltaic modules requires a full understanding of the system design, the operating environment, mechanisms that drive failure, and the duration of service that prompts a failure.

Failure is defined as the termination of the ability of a product or system to perform a required function. The primary function of a photovoltaic module is to provide safe, useful electric-power. Since modules are typically deployed as components in systems, module degradation and failure may not be immediately recognized. System design can oftentimes mask the effects of module performance degradation and/or individual module failures. Conversely, some module degradation mechanisms can significantly degrade the operation and/or performance of the entire system.

Identifying degradation mechanisms and establishing degradation rates has become increasingly important, especially in U.S. applications where photovoltaic systems are being marketed for grid-tied residential use and for building integrated photovoltaic (BIPV) applications. Owners, intent on being able to "sell back" power to their local utility, have expectations that may be affected by module degradation. BIPV consumers expect modules that will perform multiple functions. These same consumers will likely prioritize their expectations. For example BIPV owners may be more tolerant of performance degradation but less tolerant of replacement

costs for failed modules. These same owners may value aesthetics more than performance.

MODULE DEGRADATION

Information on module degradation has been collected since the early 1970's. However, the work has not been well coordinated. Minimal data generated with varied measurement techniques and analytical methods have made it difficult to facilitate a complete understanding of module degradation. For example, module performance losses of 1-2% per year were found in systems tested over a ten-year period from the mid-eighties through the mid-nineties [1]. Data from a multicrystalline module continuously exposed outdoors in open circuit configuration for eight years at Sandia shows about 0.5% per year performance loss [2]. A recent study at the National Renewable Energy Laboratory (NREL) suggests that performance of both single and multi-crystalline field-aged modules degrades about 0.7% per year, primarily due to I_{sc} losses caused by UV absorption at or near the top of the silicon surface [3]. Finally, data from the LEEE-TISO, CH-Testing Centre for Photovoltaic Modules http://leee.dct.supsi.ch/PV/Results/Tested_modules.htm, reports power degradation rates on c-Si modules ranging from 0.7%-9.8% in the first year of exposure and 0.7%-4.9% in the second year of exposure.

Lack of comprehensive performance information is not the only issue complicating the understanding of degradation. Despite continual evolution of manufacturing practices, long term stability issues such as lamination disintegration of backing material, bubbling at solder spots, fissures in backing material, module delamination, solder-joint degradation, hot spots, encapsulant discoloration, mechanical damage, and cell degradation have been recently reported [2][3][4][5][6]. An early study conducted by Ross grouped degradation into the four categories: 1) component failures, 2) power degradation, 3) module failures, and 4) life-limiting wear-out [7]. Unlike Ross, we grouped degradation observed in fielded systems into five categories that ultimately drive performance loss and possibly failure. These are: 1) degradation of packaging materials, 2) loss of adhesion, 3) degradation of cell/module interconnects, 4) degradation caused by moisture intrusion, and 5) degradation of the semiconductor device. Module degradation that falls into one of these five categories may cause performance loss without causing a failure; i.e. the module or the system continues to perform the required function. The simplest degradation/failure to define, a breach in system safety at

the array level, may occur with little associated loss of electrical performance.

Packaging Material Degradation

Module package degradation occurs when the laminate package is damaged or packaging materials degrade during normal service, affecting the function and/or integrity of the module. Examples of packaging degradation include glass breakage, dielectric breakdown, bypass diode failure, encapsulant discoloration, and backsheet cracking and/or delamination. Package degradation can cause module performance failures, which can lead to system level issues like array performance failure, safety hazards, and/or failure of a supplemental function, e.g. a module functioning as a window in a BIPV application.

Modules that incur packaging damage introduce the possibility of ground faults and/or excessive module leakage current. Additionally, packaging damage can introduce safety hazards into high voltage systems by failing to provide insulation necessary to prevent electric shock as well as creating pathways for electrochemical corrosion. The potential for a shock hazard can be further increased by moisture intrusion into the package. Fig. 1 shows an example of module breakage that introduced a safety problem shortly after installation.



Fig. 1. Glass breakage can present a high-voltage safety problem but still provide useful power.

Adhesional Degradation

Delamination is defined as the breakdown of the bonds between material layers that constitute a module laminate. Field experience has shown that front-side delamination at the glass/encapsulant and cell/encapsulant interfaces is more common than backside delamination. Front-side delamination causes optical decoupling of materials that transmit sunlight to the cells, resulting in performance degradation. Delamination on either side interrupts efficient heat dissipation and increases the possibility of reverse-bias cell heating. Higher cell operating temperatures cause performance degradation. Fig. 2 shows an infrared image of a short-circuited module with what appears to be reverse-bias cell heating and coincidentally a large delaminated area over that cell.

Delamination contributed to the $>30^{\circ}\text{C}$ temperature difference between the hot spot and the rest of the module by reducing the heat transfer efficiency at the delaminated area. Delamination effects on moisture intrusion and retention are discussed later in this paper.

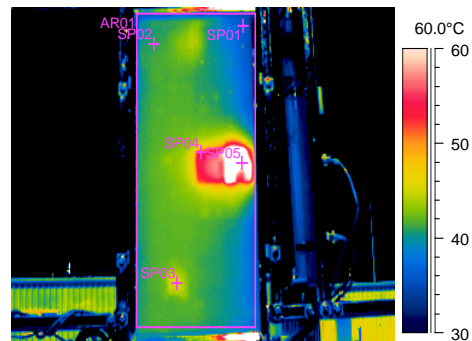


Fig. 2 Delamination causes poor heat transfer in addition to optical decoupling.

Interconnect Degradation

Interconnect degradation in crystalline silicon modules occurs when the joined cell-to-ribbon or ribbon-to-ribbon area changes in structure or geometry. “Coarsening”, a change in joint structure, occurs as a result of segregation of the metals (SnPb) in the soldering alloy. Coarsening causes the formation of larger metal grains that undergo thermomechanical fatigue, enhancing the possibility of cracking at the grain boundaries and possible joint failure. Fig. 3 shows solder-joint cross sections from two different modules. The top joint exhibits coarsening after twenty years but due to the robust design and soldering process, no signs of thermomechanical stress were seen [6]. The bottom joint (five-years-old) in Fig. 3 exhibited coarsening as well as an enhanced potential for cracking due to voids and poor wetting.

Changes in solder-joint geometry caused by thermomechanical fatigue reduce the number of redundant solder-joints in a module causing decreased performance. These changes occur due to cracks that develop at high stress concentrations, such as voids and thread-like joints. This leads to increased series resistance as current is forced to circulate through diminished solder-joint area and ultimately fewer solder-joints. Interconnect ribbon fatigue has caused degradation in the past but there have been no recent observations of this problem in field-aged modules. Characteristics directly attributable to interconnect degradation include increased series resistance in the electrical circuit, increased heating in the module, and localized hot spots causing burns at the solder-joints, the polymer backsheet, and in the encapsulant.

Interconnect degradation in thin-film modules is distinctively different. Observations of field-aged modules have found that a prime location for continuity failure is the point where the junction-box interconnect strap bonds to the cell frit. This is a very vulnerable solder bond that is likely to incur thermomechanical fatigue as a result of daily thermal cycling.

Thin-film module scribe-line problems emerge when either the SnO_2 cell isolation scribe-lines or the back metal cell isolation scribe lines do not have the material completely removed. In either case, partially shunted cells are the result. Another scribe-line problem occurs when cell adhesion to the tin-oxide conductive layer is low. A separation at this line presents an ideal place for initiation of crack failures, resulting in localized heating that further promotes crack propagation.

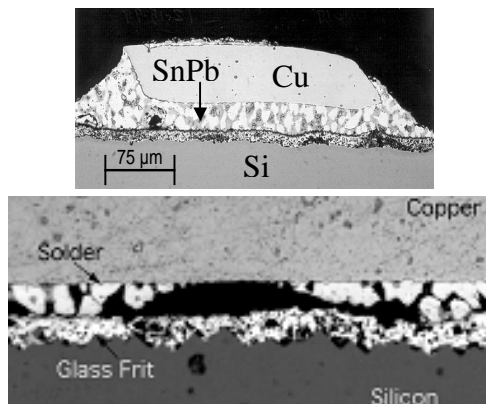


Fig. 3. Solder-joints from two field-aged modules show some coarsening. The 20-year-old joint (top) was more robust while the bottom joint showed voids and dewetting.

Moisture Intrusion

Moisture permeation through the module backsheet or through edges of module laminates causes corrosion and increases leakage currents. Corrosion attacks cell metallization in crystalline silicon modules and semiconductor layers in thin-film modules, causing loss of electrical performance. Fig. 4 shows moisture-induced corrosion that caused gridline adhesion to the silicon cell to fail. Retention of moisture in module packaging materials increases material electrical conductivity. This causes increased leakage current and subsequent performance loss. Moisture intrusion has also been linked to loss of adhesional strength at bond interfaces in the module laminate. Moisture intrusion combined with damaged module packaging materials can introduce severe safety concerns in high voltage applications.

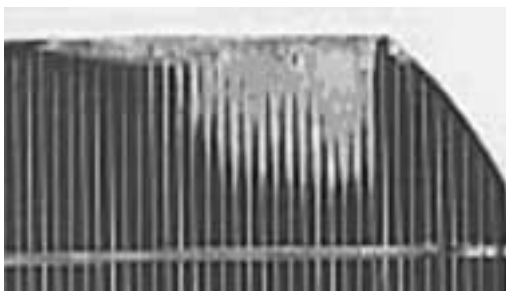


Fig. 4. Moisture induced corrosion that caused bonds between the grid lines and the cell to fail.

Semiconductor Device Degradation

Degradation of the semi-conductor material itself can also contribute to performance loss in field-aged modules. Crystalline silicon modules now have a long track record of performance stability in the field. This stability, in part, is due to the stability of the semiconductor material (crystalline silicon) used to make the cells. Field experience has indicated that the primary causes for performance loss in these modules have been associated with mechanisms external to the cells such as solder bonds, encapsulant browning, delamination and interconnect issues. Initial light induced degradation (LID) is one of the few changes that can be attributed to the c-Si semiconductor device. The LID effect is limited to the first few hours of outdoor module exposure and results in a 1-5% loss in short-circuit current [8]. This effect has been frequently quantified by test laboratories and module manufacturers, but has not historically been documented in the open literature other than very recently.

Another form of degradation in crystalline cells is a result of chemically assisted diffusion of cell dopant (phosphorous) to the cell surface. High concentrations of phosphorous, along with sodium migrating from soda lime glass superstrates to the cell surface, have always correlated to low adhesional strength at the cell/encapsulant interface. Furthermore, it has been reported that loss of adhesional strength is exacerbated by exposure to high humidity environments [9] [10].

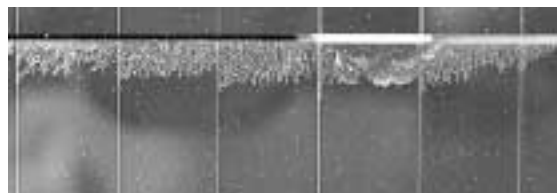


Fig. 5. Field exposed a-Si module exhibits electrochemical corrosion occurring at the scribe-line.

Cracking is a cell level failure mechanism that has historically been found in modules. The degree of cell cracking and resulting electrical isolation dictates the level of associated performance loss. Improvements in manufacturing practices have minimized the occurrence of cracked cells.

Degradation and/or stabilization of a-Si modules have been the subject of many studies but there continues to be a lack of complete understanding of the mechanisms and environmental influences that cause performance degradation. [11] [12]. Field-aged a-Si modules that have a transparent conductive oxide (TCO) deposited on the soda-lime glass superstrate have demonstrated electrochemical corrosion, Fig. 5. This failure mechanism has been duplicated in accelerated laboratory tests conducted at NREL [13]. Contributors to the corrosion include sodium migration from the soda-lime glass, water vapor, and internal electric fields. It has also been suggested that the presence of moisture accelerates the onset and progression of the corrosion [13].

A review of the status of thin-film photovoltaic technologies in 1997 suggested that degradation mechanisms in CdTe

and CIS modules would be subtle with long-term effects possible [14]. Recent data from fielded CdTe and CIS applications suggests higher than expected performance degradation and potential for system level failures. While the data on this reliability issue is proprietary, studies have been initiated in order to identify the degradation source(s). As commercial production of thin-film technologies scales up and larger thin-film arrays are deployed, we expect to learn more about the reliability of thin film modules. Sandia, with assistance from its partners, Florida Solar Energy Center (FSEC), Southwest Technology Development Institute (SWTDI) and the National Renewable Energy Laboratory (NREL), is currently conducting a Module Long Term Exposure (MLTE) program that tests commercially available modules representative of all photovoltaic technologies. This controlled long-term exposure will provide technology specific information on field-induced module degradation.

SUMMARY

Comprehensive studies of field-aged modules must be conducted to better understand degradation mechanisms and, more importantly, to define degradation rates. Most studies of degradation have been conducted on failed modules and results have been compared to limited baseline and field-aged module information. Minimal studies have been conducted on healthy field-aged modules to establish the factors surrounding their satisfactory performance. Data needed to establish performance degradation rates needs to come from multiple sources with well-coordinated test procedures. Progress toward understanding and solving the more complex long-term degradation mechanisms has been slow. A greater understanding of the factors that initiate module degradation and cause the progression toward failure is needed. Once this information is understood, it can be applied to system level models to properly quantify the effects on overall system performance, reliability, and cost.

ACKNOWLEDGEMENTS

This paper is the culmination of several years of module reliability studies performed by Sandia National Laboratories, National Renewable Energy Laboratory, Florida Solar Energy Center, Southwest Technology Development Institute and the many photovoltaic manufacturers who have collaborated with us. The authors would specifically like to thank Dr. Neelkanth Dhere who has been an integral part of this effort since 1995. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation a Lockheed Martin subsidiary, for the U.S. Department of Energy under contract # DE-AC04-94AL85000

REFERENCES

- [1] M.G. Thomas et al., *A Ten-Year Review of Performance of Photovoltaic Systems*, Proc. NREL Photovoltaic Performance and Reliability Workshop, NREL/CP-411-7414, 1994 pp 279-285.
- [2] D.L. King, M.A. Quintana, J.A. Kratochvil, D.E. Ellibee, and B.R. Hansen, *Photovoltaic Module Performance and Durability Following Long-Term Field Exposure*, Progress in Photovoltaics Research and Applications July-August 2000, pp. 241-256
- [3] C.R. Osterwald, A. Anderberg, S. Rummel, and L. Ottoson; *Degradation Analysis of Weathered Crystalline-Silicon PV Modules*, 29th IEEE PVSC, 2002
- [4] G. Schaur; *Long Term Stability of PV-Modules, Damage Cases and Damage Analyses*, 16th European Photovoltaic Solar Energy Conference and Exhibition, May 2000
- [5] J. Bernreuter and M. Schmela, *Blue Turns Milky White*; Photon International, June 2001 pp. 16-17
- [6] M.A. Quintana, D.L. King, F.M. Hosking, J.K. Kratochvil, R.W. Johnson, B. R. Hansen, N.G. Dhere and M. B. Pandit; *Diagnostic Analysis of Silicon Photovoltaic Modules After 20-Year Field Exposure*, 28th IEEE PVSC, 2000, pp. 1420-1423
- [7] R.G. Ross, *Technology Developments Toward 30-Year Life of Photovoltaic Modules*, 17th IEEE PVSC, 1984
- [8] T. Saitoh, H. Hashigami, S. Rein, S. Glunz, *Overview of Light Degradation Research on Crystalline Silicon Solar Cells*, Progress in PV: Research and Applications, 8, 2000, pp. 537-547
- [9] N.G. Dhere, *PV Module Durability in Hot and Dry Climate*, 16th European Photovoltaic Solar Energy Conference, May 2000
- [10] N.G. Dhere, and M.B. Pandit, *Study of Delamination in Acceleration Tested PV Modules*, 17th European Photovoltaic Solar Energy Conference, October 2001
- [11] D.L. King, J.A. Kratochvil, and W.E. Boyson, *Stabilization and Performance Characteristics of Commercial Amorphous-Silicon PV Modules*, 28th IEEE PVSC 2000, pp. 1446-1449
- [12] C.R. Wronski, *Amorphous Silicon Photovoltaics: Order from Disorder*, 28th IEEE PVSC 2000; pp. 1-6
- [13] C.R. Osterwald, T.J. McMahon, J.A. del Cueto; *Electrochemical Corrosion of SnO₂:F Transparent Conducting Layers in Thin Film Photovoltaic Modules*, Submitted to Solar Energy Materials and Solar Cells
- [14] H.S. Ullal, K. Zweibel, and B von Roedern, *Current Status of Polycrystalline Thin-Film Module Technologies*, 26th IEEE PVSC, 1997 pp. 301-305